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(54) **METHODS FOR MANUFACTURING CUSTOMIZED ANTENNA STRUCTURES**

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H01Q 9/42 (2006.01)

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CPC ***H01Q 1/243*** (2013.01); ***H01Q 9/42*** (2013.01); *Y10T 29/49004* (2015.01)

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USPC .... 29/600, 592.1, 601; 343/700 MS, 702, 343/720, 795, 872
See application file for complete search history.

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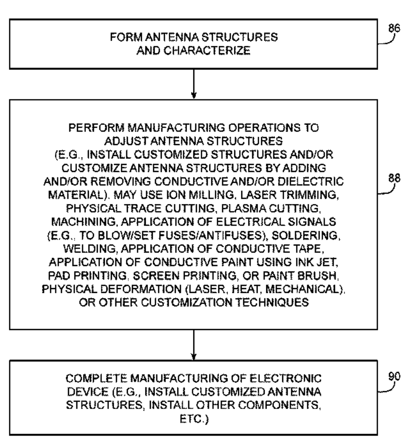
(57) **ABSTRACT**

Antenna structures may be customized to compensate for manufacturing variations in electronic device antennas. The antenna structures may include an antenna resonating element and a ground. Customizations may be made to the antenna structures by performing customization operations such as adding material, removing material, deforming material, and making electrical adjustments. Customizations may be performed to a conductive antenna resonating element structure, to a ground structure, or to associated antenna structures such as parasitic antenna elements. During manufacturing operations, antenna structures may be characterized by making radio-frequency antenna performance measurements. Antenna performance can be compared to desired performance levels and compensating customizations for the antenna structures can be identified. Customized antenna structures can be installed in electronic devices during manufacturing to produce devices that meet desired specifications.

18 Claims, 8 Drawing Sheets



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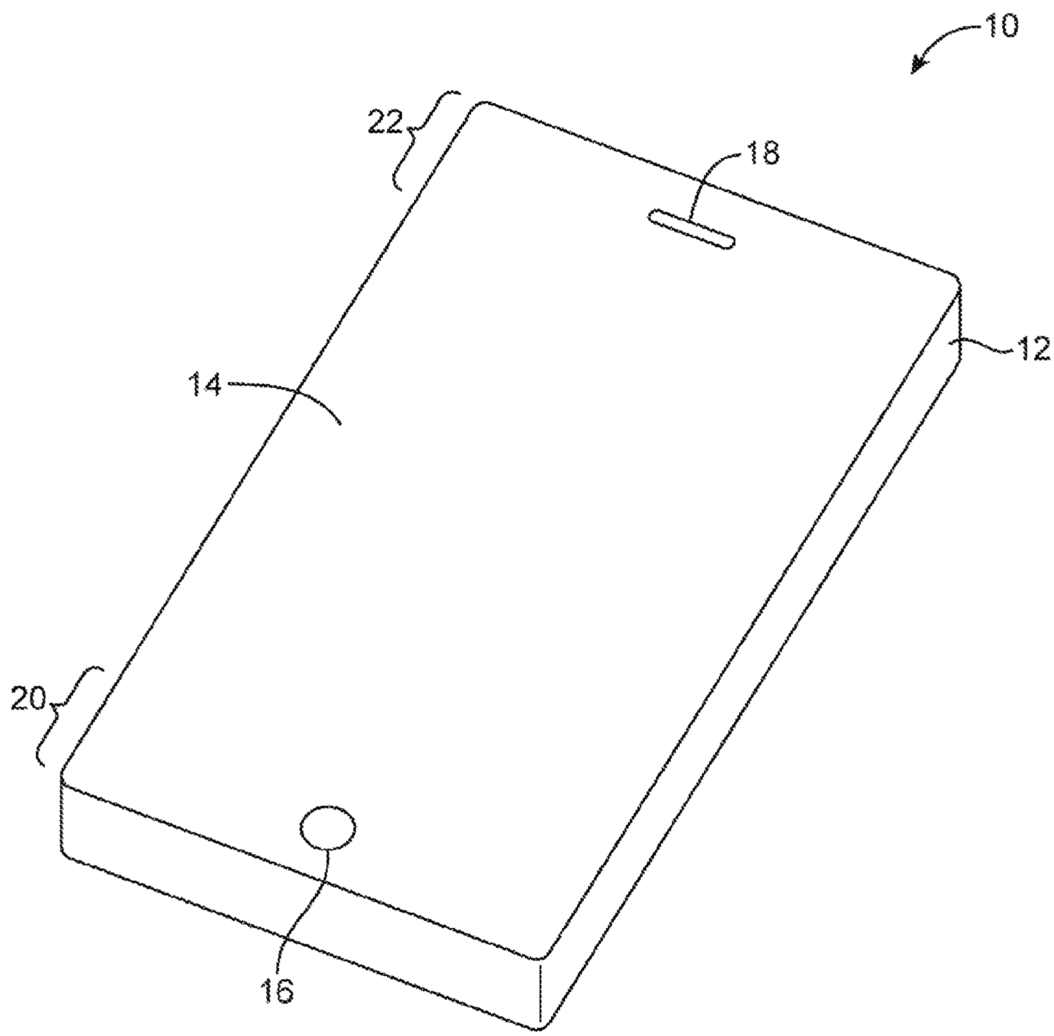

FIG. 1

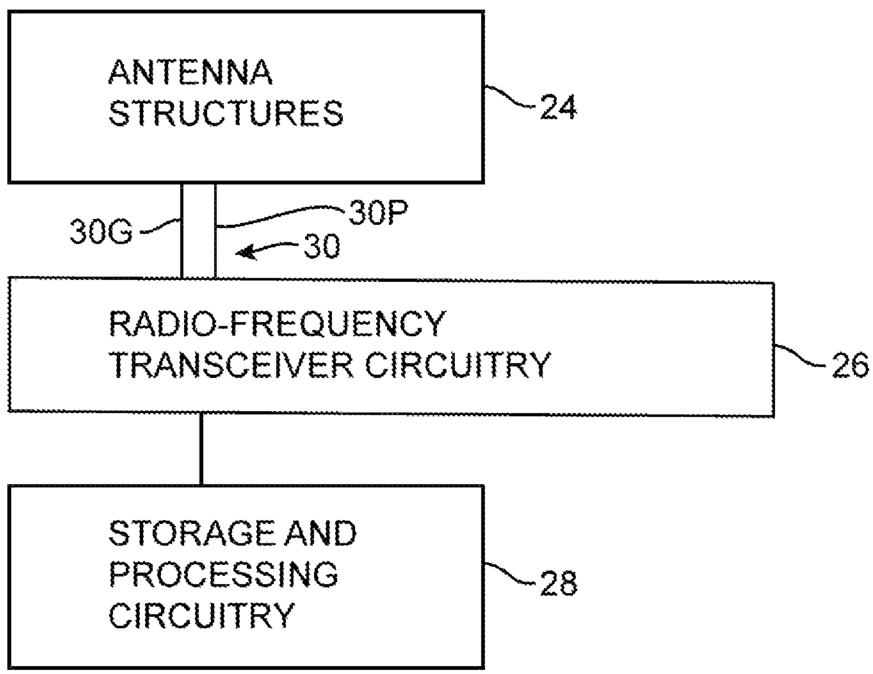
ANTENNA
STRUCTURES
24
30G
30P
30
RADIO-FREQUENCY
TRANSCEIVER CIRCUITRY
26
STORAGE AND
PROCESSING
CIRCUITRY
28

FIG. 2

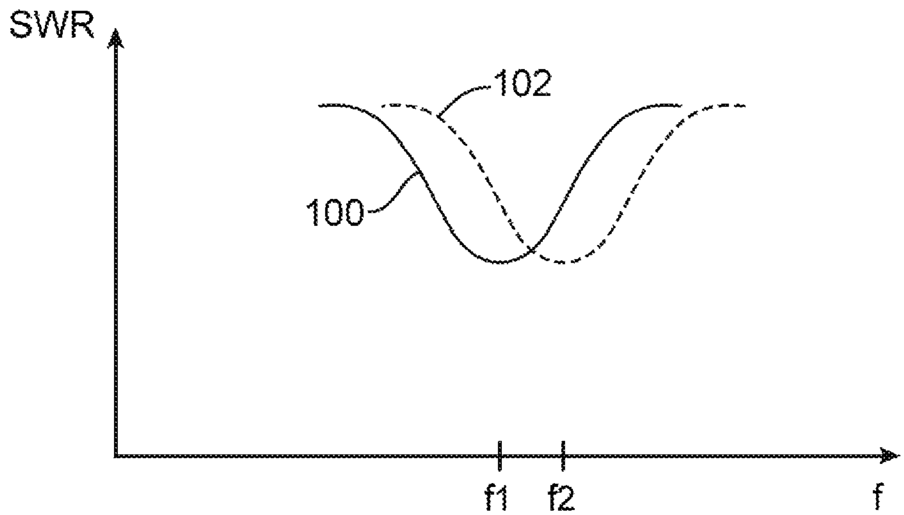

FIG. 3

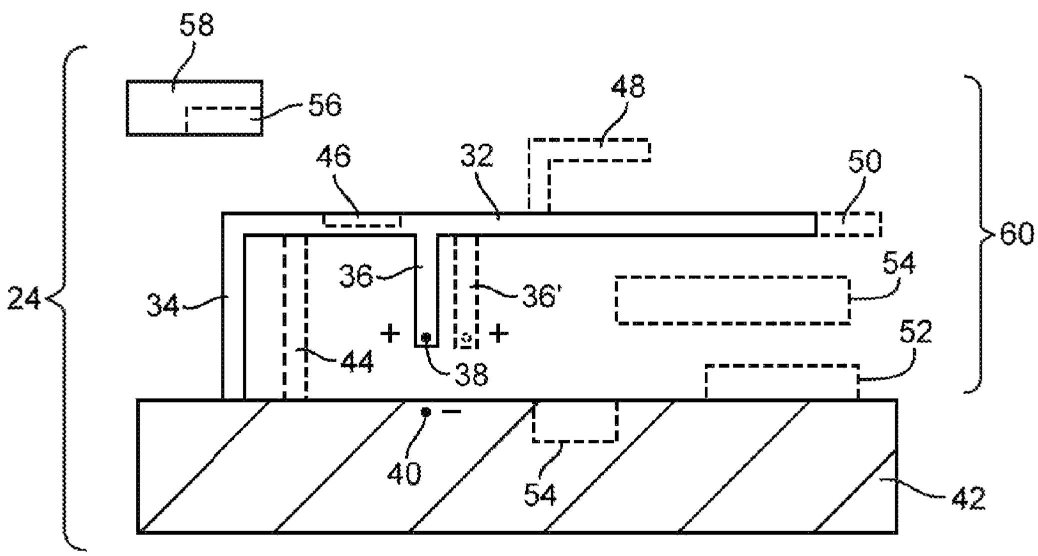

FIG. 4

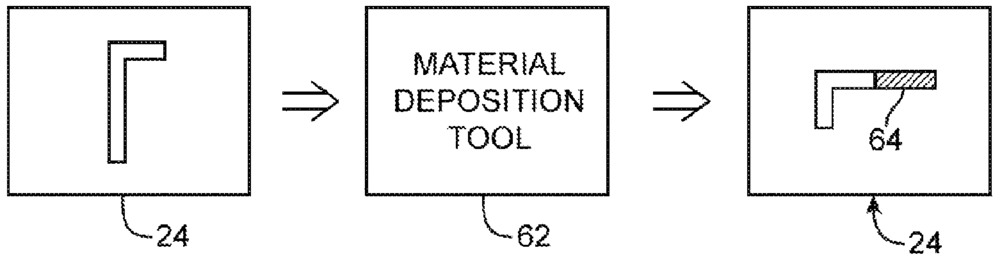

FIG. 5

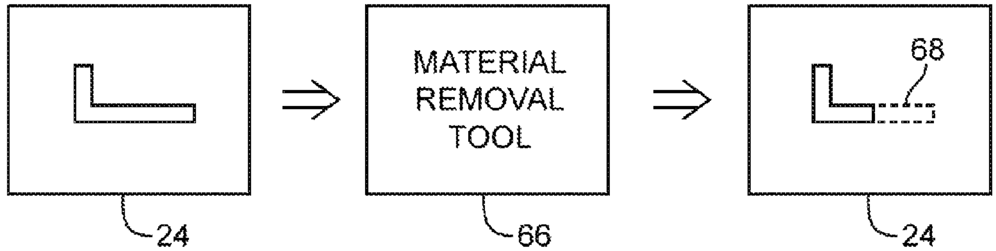

FIG. 6

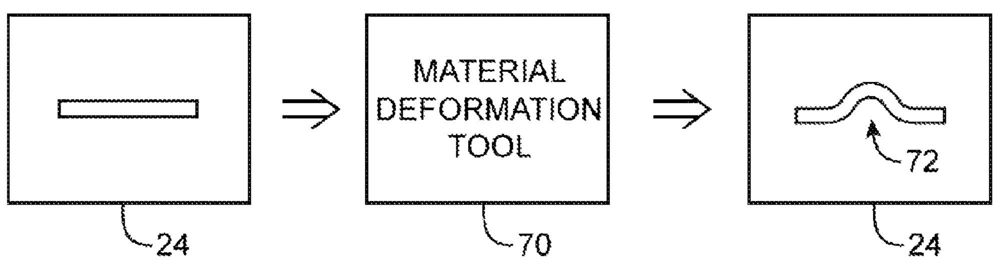

FIG. 7

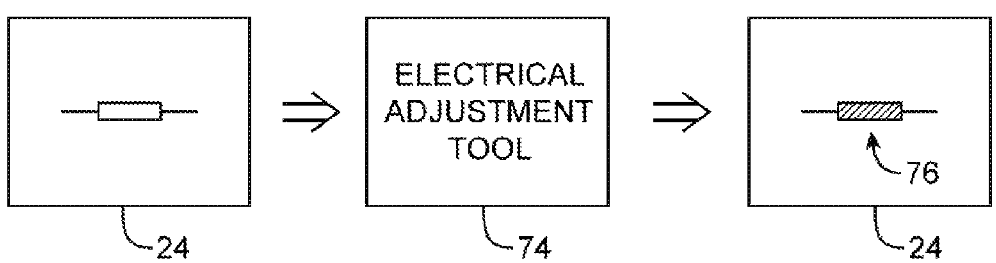

FIG. 8

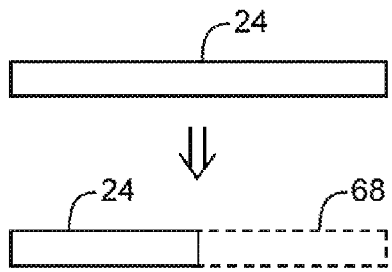

FIG. 9

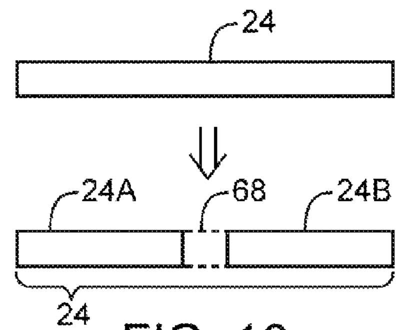

FIG. 10

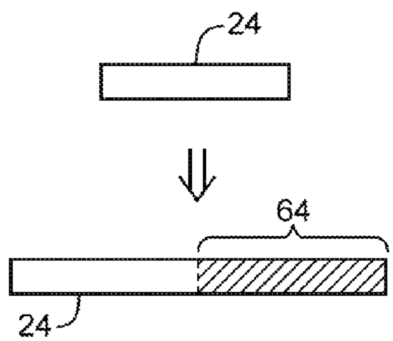

FIG. 11

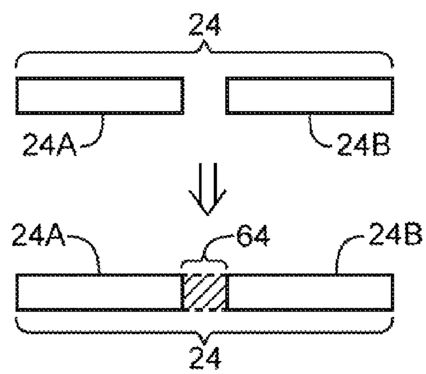

FIG. 12

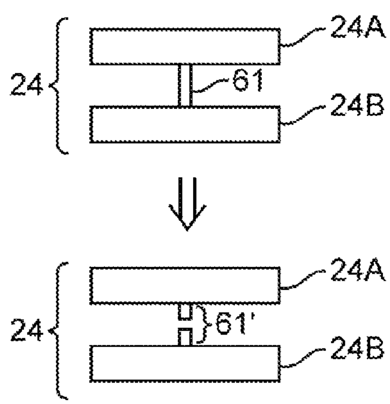

FIG. 13

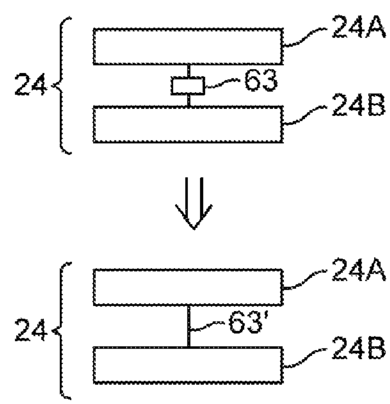

FIG. 14

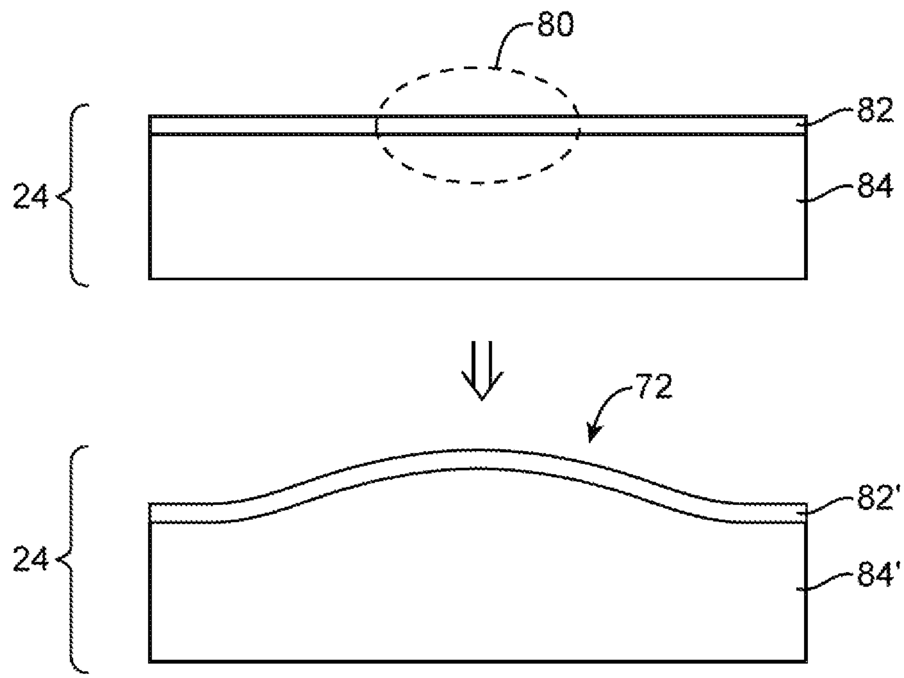

FIG. 15

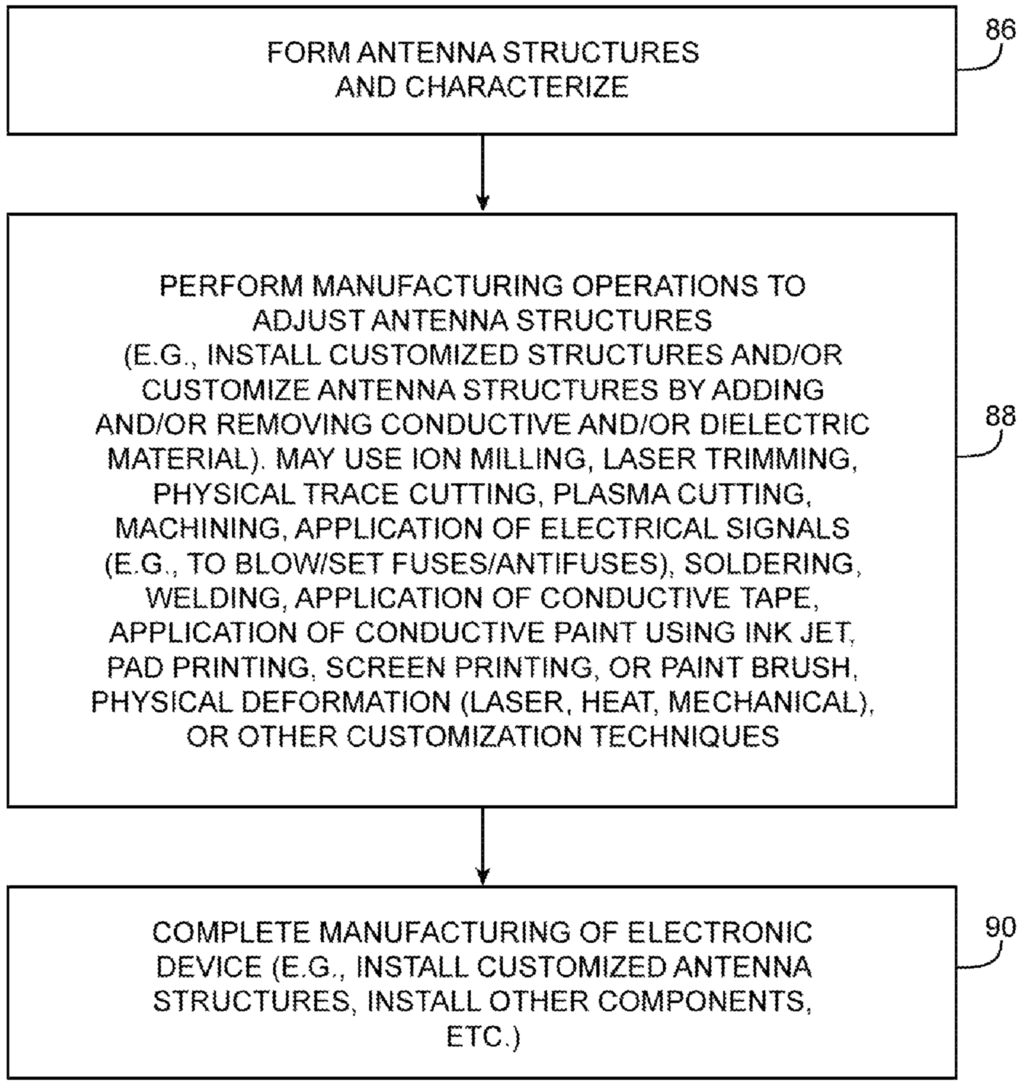
FORM ANTENNA STRUCTURES AND CHARACTERIZE
86
PERFORM MANUFACTURING OPERATIONS TO ADJUST ANTENNA STRUCTURES (E.G., INSTALL CUSTOMIZED STRUCTURES AND/OR CUSTOMIZE ANTENNA STRUCTURES BY ADDING AND/OR REMOVING CONDUCTIVE AND/OR DIELECTRIC MATERIAL). MAY USE ION MILLING, LASER TRIMMING, PHYSICAL TRACE CUTTING, PLASMA CUTTING, MACHINING, APPLICATION OF ELECTRICAL SIGNALS (E.G., TO BLOW/SET FUSES/ANTIFUSES), SOLDERING, WELDING, APPLICATION OF CONDUCTIVE TAPE, APPLICATION OF CONDUCTIVE PAINT USING INK JET, PAD PRINTING, SCREEN PRINTING, OR PAINT BRUSH, PHYSICAL DEFORMATION (LASER, HEAT, MECHANICAL), OR OTHER CUSTOMIZATION TECHNIQUES
88
COMPLETE MANUFACTURING OF ELECTRONIC DEVICE (E.G., INSTALL CUSTOMIZED ANTENNA STRUCTURES, INSTALL OTHER COMPONENTS, ETC.)
90

FIG. 16

METHODS FOR MANUFACTURING CUSTOMIZED ANTENNA STRUCTURES

BACKGROUND

This relates generally to electronic devices, and more particularly, to electronic devices that have antennas.

Electronic devices such as computers and handheld electronic devices are often provided with wireless communications capabilities. For example, electronic devices may use long-range wireless communications circuitry such as cellular telephone circuitry to communicate using cellular telephone bands. Electronic devices may use short-range wireless communications links to handle communications with nearby equipment. For example, electronic devices may communicate using the WiFi® (IEEE 802.11) bands at 2.4 GHz and 5 GHz and the Bluetooth® band at 2.4 GHz.

Antenna performance can be critical to proper device operation. Antennas that are inefficient or that are not tuned properly may result in dropped calls, low data rates, and other performance issues. There are limits, however, to how accurately conventional antenna structures can be manufactured.

Many manufacturing variations are difficult or impossible to avoid. For example, variations may arise in the size and shape of printed circuit board traces, variations may arise in the density and dielectric constant associated with printed circuit board substrates and plastic parts, and conductive structures such as metal housing parts and other metal pieces may be difficult or impossible to construct with completely repeatable dimensions. Some parts are too expensive to manufacture with precise tolerances and other parts may need to be obtained from multiple vendors, each of which may use a different manufacturing process to produce its parts.

Manufacturing variations such as these may result in undesirable variations in antenna performance. An antenna may, for example, exhibit an antenna resonance peak at a first frequency when assembled from a first set of parts, while exhibiting an antenna resonance peak at a second frequency when assembled from a second set of parts. If the resonance frequency of an antenna is significantly different than the desired resonance frequency for the antenna, a device may need to be scrapped or reworked.

It would therefore be desirable to provide a way in which to address manufacturability issues such as these so as to make antenna designs more amenable to reliable mass production.

SUMMARY

An electronic device may be provided with antenna structures. Due to manufacturing variations, the performance of the antenna structures as initially manufactured may deviate from desired performance levels.

To manufacture electronic devices with antenna structures that perform as desired, the antenna structures that are initially manufactured may be characterized using test equipment. Based on these characterizations, deviations between measured antenna performance and desired antenna performance may be identified and corresponding customizations for the antenna structures to compensate for these deviations may be identified.

The antenna structures may be processed to implement the identified customizations. For example, the antenna structures can be processed to remove material, to add material, to deform material, to apply electrical signals to adjust components such as fuses and antifuses, or to otherwise customize the antenna structures.

Once the customizations have been made to the antenna structures, the antenna structures and remaining device components can be assembled to form a completed electronic device.

Further features of the invention, its nature and various advantages will be more apparent from the accompanying drawings and the following detailed description of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an illustrative electronic device with customized antenna structures in accordance with an embodiment of the present invention.

FIG. **2** is a schematic diagram of an illustrative electronic device with customized antenna structures in accordance with an embodiment of the present invention.

FIG. **3** is graph showing how antenna performance can be adjusted by customizing antenna structures in accordance with an embodiment of the present invention.

FIG. **4** is a diagram of an illustrative antenna structures showing how the antenna structures may be customized in accordance with an embodiment of the present invention.

FIG. **5** is a diagram showing how a material deposition tool may be used to customize antenna structures by adding material to the structures in accordance with an embodiment of the present invention.

FIG. **6** is a diagram showing how a material removal tool may be used to customize antenna structures by removing material from the structures in accordance with an embodiment of the present invention.

FIG. **7** is a diagram showing how a material deformation tool may be used to customize antenna structures by deforming material in the structures in accordance with an embodiment of the present invention.

FIG. **8** is a diagram showing how an electrical adjustment tool such as a computer-based controller may be used to customize antenna structures by applying electrical signals to the antenna structures in accordance with an embodiment of the present invention.

FIG. **9** is a diagram showing how a material removal tool may be used to customize antenna structures by removing a portion of an antenna structure to form a structure with a reduced size in accordance with an embodiment of the present invention.

FIG. **10** is a diagram showing how a material removal tool may be used to customize antenna structures by removing a portion of an antenna structure to create an open circuit between separate portions of the antenna structure in accordance with an embodiment of the present invention.

FIG. **11** is a diagram showing how a material deposition tool may be used to customize antenna structures by adding material to the antenna structures to create larger structures in accordance with an embodiment of the present invention.

FIG. **12** is a diagram showing how a material deposition tool may be used to customize antenna structures by adding material to antenna structures to create a short circuit that electrically joins separate portions of the antenna structures together to form a unified antenna structure in accordance with an embodiment of the present invention.

FIG. **13** is a diagram showing how an electrical adjustment tool may be used to customize antenna structures by electrically adjusting a component such as a fuse to create an open circuit between portions of the antenna structure in accordance with an embodiment of the present invention.

FIG. **14** is a diagram showing how an electrical adjustment tool may be used to customize antenna structures by electrically adjusting a component such as an antifuse to create a short circuit that electrically joins separate portions of the antenna structures together to form a unified antenna structure in accordance with an embodiment of the present invention.

FIG. **15** is a diagram showing how a material deformation tool may be used to customize antenna structures by deforming material in the structures in accordance with an embodiment of the present invention.

FIG. **16** is a flow chart of illustrative steps involved in characterizing antenna performance and compensating for manufacturing variations by customizing antenna structures in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

An illustrative electronic device of the type that may be provided with custom antenna structures to compensate or manufacturing variations is shown in FIG. **1**. Electronic devices such as illustrative electronic device **10** of FIG. **1** may be laptop computers, tablet computers, cellular telephones, media players, other handheld and portable electronic devices, smaller devices such as wrist-watch devices, pendant devices, headphone and earpiece devices, other wearable and miniature devices, or other electronic equipment.

As shown in FIG. **1**, device **10** includes housing **12**. Housing **12**, which is sometimes referred to as a case, may be formed of materials such as plastic, glass, ceramics, carbon-fiber composites and other fiber-based composites, metal, other materials, or a combination of these materials. Device **10** may be formed using a unibody construction in which most or all of housing **12** is formed from a single structural element (e.g., a piece of machined metal or a piece of molded plastic) or may be formed from multiple housing structures (e.g., outer housing structures that have been mounted to internal frame elements or other internal housing structures).

Device **10** may, if desired, have a display such as display **14**. Display **14** may be a touch screen that incorporates capacitive touch electrodes or other touch sensors or may be touch insensitive. Display **14** may include image pixels formed from light-emitting diodes (LEDs), organic LEDs (OLEDs), plasma cells, electronic ink elements, liquid crystal display (LCD) pixels, or other suitable image pixel structures. A cover layer such as a cover glass member or a transparent planar plastic member may cover the surface of display **14**. Buttons such as button **16** may pass through openings in the cover layer. Openings may also be formed in the glass or plastic display cover layer of display **14** to form a speaker port such as speaker port **18**. Openings in housing **12** may be used to form input-output ports, microphone ports, speaker ports, button openings, etc.

Housing **12** may include a rear housing structure such as a planar glass member, plastic structures, metal structures, fiber-composite structures, or other structures. Housing **12** may also have sidewall structures. The sidewall structures may be formed from extended portions of the rear housing structure or may be formed from one or more separate members. Housing **12** may include a peripheral housing member such as a peripheral conductive housing member that runs along some or all of the rectangular periphery of device **10**. The peripheral conductive housing member may form a bezel that surrounds display **14**. If desired, the peripheral conductive member may be implemented using a metal band or other conductive structure that forms conductive vertical sidewalls for housing **12**. Peripheral conductive housing members or other housing structures may also be used in device **10** to form curved or angled sidewall structures or housings with other suitable shapes. A peripheral conductive member may be formed from stainless steel, other metals, or other conductive materials. In some configurations, a peripheral conductive member in device **10** may have one or more dielectric-filled gaps. The gaps may be filled with plastic or other dielectric materials and may be used in dividing the peripheral conductive member into segments. The shapes of the segments of the peripheral conductive member may be chosen to form antennas with desired antenna performance characteristics (e.g., inverted-F antenna structures or loop antenna structures with desired frequency resonances).

Wireless communications circuitry in device **10** may be used to form remote and local wireless links. One or more antennas may be used during wireless communications. Single band and multiband antennas may be used. For example, a single band antenna may be used to handle local area network communications at 2.4 GHz (as an example). As another example, a multiband antenna may be used to handle cellular telephone communications in multiple cellular telephone bands. Antennas may also be used to receive global positioning system (GPS) signals at 1575 MHz in addition to cellular telephone signals and/or local area network signals. Other types of communications links may also be supported using single-band and multiband antennas.

Antennas may be located at any suitable locations in device **10**. For example, one or more antennas may be located in an upper region such as region **22** and one or more antennas may be located in a lower region such as region **20**. If desired, antennas may be located along device edges, in the center of a rear planar housing portion, in device corners, etc.

Antennas in device **10** may be used to support any communications bands of interest. For example, device **10** may include antenna structures for supporting local area network communications (e.g., IEEE 802.11 communications at 2.4 GHz and 5 GHz for wireless local area networks), signals at 2.4 GHz such as Bluetooth® signals, voice and data cellular telephone communications (e.g., cellular signals in bands at frequencies such as 700 MHz, 850 MHz, 900 MHz, 1800 MHz, 1900 MHz, 2100 MHz, etc.), global positioning system (GPS) communications at 1575 MHz, signals at 60 GHz (e.g., for short-range links), etc.

A schematic diagram showing illustrative components that may be used in supporting wireless communications in device **10** of FIG. **1** is shown in FIG. **2**. As shown in FIG. **2**, device **10** may include storage and processing circuitry **28**. Storage and processing circuitry **28** may include storage such as hard disk drive storage, nonvolatile memory (e.g., flash memory or other electrically-programmable-read-only memory configured to form a solid state drive), volatile memory (e.g., static or dynamic random-access-memory), etc. Processing circuitry in storage and processing circuitry **28** may be used to control the operation of device **10**. This processing circuitry may be based on one or more microprocessors, microcontrollers, digital signal processors, application specific integrated circuits, baseband processors, etc. Input-output circuitry such as user interface components may be coupled to storage and processing circuitry **28**.

Radio-frequency transceiver circuitry **26** may transmit and receive radio-frequency signals using antenna structures **24**. Radio-frequency transceiver circuitry **26** may include transceiver circuitry that handles 2.4 GHz and 5 GHz bands for WiFi® (IEEE 802.11) communications, the 2.4 GHz Bluetooth® communications band, and wireless communications in cellular telephone bands at 700 MHz, 850 MHz, 900 MHz, 1800 MHz, 1900 MHz, and 2100 MHz (as examples). Circuitry **26** may also include circuitry for other short-range and long-range wireless links. For example, transceiver circuitry

26 may be used in handling signals at 60 GHz. If desired, transceiver circuitry **26** may include global positioning system (GPS) receiver equipment for receiving GPS signals at 1575 MHz or for handling other satellite positioning data.

Radio-frequency transceiver circuitry **26** may be coupled to antenna structures **24** using a transmission line such as transmission line **30**. Transmission line **30** may include a positive signal conductor such as conductor (path) **30**P and a ground signal conductor (path) **30**G. Paths **30**P and **30**G may be formed on rigid and flexible printed circuit boards, may be formed on dielectric support structures such as plastic, glass, and ceramic members, may be formed as part of a cable, etc. Transmission line **30** may be formed using one or more microstrip transmission lines, stripline transmission lines, edge coupled microstrip transmission lines, edge coupled stripline transmission lines, coaxial cables, or other suitable transmission line structures.

Radio-frequency front end circuitry (e.g., switches, impedance matching circuitry, radio-frequency filters, and other circuits) may be interposed in the signal path between radio-frequency transceiver circuitry **26** and the antennas in device **10** if desired.

Antenna structures **24** may include one or more antennas of any suitable type. For example, the antennas may include antennas with resonating elements that are formed from loop antenna structure, patch antenna structures, inverted-F antenna structures, slot antenna structures, planar inverted-F antenna structures, helical antenna structures, hybrids of these designs, etc. Different types of antennas may be used for different bands and combinations of bands. For example, one type of antenna may be used in forming a local wireless link antenna and another type of antenna may be used in forming a remote wireless link antenna.

Due to manufacturing variations, antenna structures **24** may not always perform exactly within desired specifications when initially manufactured. For example, an antenna assembly that is formed from a peripheral conductive housing member in device **10** may be subject to performance variations that result from manufacturing variations in the peripheral conductive housing member. To ensure that each finished electronic device that is manufactured performs satisfactorily, antenna structures **24** may be characterized and customized accordingly to compensate for detected variations as part of the manufacturing process. As an example, trimming equipment may be used to trim metal parts in antenna structures **24** as part of the manufacturing process or other manufacturing equipment may be used to make antenna structure adjustments. Customization operations such as these may ensure that all completed devices that are shipped to users performed as expected, even when manufacturing variations in device components are present.

A graph showing how customization techniques may be used to compensate for manufacturing variations is shown in FIG. **3**. In the graph of FIG. **3**, antenna performance for illustrative antenna structures **24** of FIG. **2** has been characterized by plotting standing wave ratio (SWR) for antenna structures **24** as a function of operating frequency f. Due to manufacturing variations, antenna structures **24** in the FIG. **3** example are initially characterized by performance curve **100** and exhibit a frequency response peak at frequency f**1**, which is lower than a desired operation frequency of frequency f**2**. Because antenna performance is not satisfactory using antenna structures **24** as originally fabricated, appropriate customization operations may be performed on antenna structures **24**. Following customization, the antenna structures may be characterized by performance curve **102** of FIG. **3** and may exhibit a frequency response peak at frequency f**2**, which is the desired frequency of operation.

FIG. **4** is a diagram showing illustrative ways in which antenna structures **24** may be customized. In general, any type of antenna or antennas may be used in forming antenna structures **24**. In the example of FIG. **4**, antenna structures **24** have been based on an inverted-F antenna design. The inverted-F antenna structures of FIG. **4** have ground plane **42** and inverted-F antenna resonating element **60**. Inverted-F antenna resonating element **60** may have a main resonating element arm such as arm **32**. A short circuit branch such as short circuit branch **34** may be used to couple arm **32** to ground plane **42**. Antenna resonating element feed branch **36** may be coupled to positive antenna feed terminal **38**. Ground antenna feed terminal **40** may be coupled to ground plane **42**. Antenna feed terminals **38** and **40** may form an antenna feed for the inverted-F antenna.

The configuration of the structures such as structures that make up ground plane **42** and the structures that make up antenna resonating element **60** may affect antenna performance. Accordingly, adjustments to the conductive structures (and dielectric structures) of antenna structures **24** may be used to tune antenna structures **24** so that desired performance criteria are satisfied. If, for example, the frequency response of the inverted-F antenna is not as desired, customizing adjustments to antenna structures **24** may be made to lengthen or shorten antenna resonating element arm **32** (as an example). Adjustments may also be made to the structures that make up the antenna feed for the antenna, the structures that make up ground plane **42**, parasitic antenna structures, etc.

As shown in FIG. **4**, for example, adjustments may be made to antenna structures **24** to lengthen antenna resonating element arm **32** (see, e.g., illustrative added conductive material **50** at the tip of arm **32**). As shown by dashed line **36'**, the position of antenna feed structure **36** may be adjusted. Dashed line **34'** shows how the position of short circuit branch **34** may be adjusted. If desired, conductive structures may be added that change the shapes of antenna components. For example, additional conductive material such as portion **48** may be added to antenna resonating element arm **32** to adjust the performance of antenna resonating element **60** and antenna structures **24**. If desired, ground plane **42** may be modified to adjust antenna structures **24**. For example, material may be removed from ground plane **42** (as indicated by dashed line **54**) or may be added to ground plane **42** (as indicated by dashed line **52**). In some situations, the performance of an antenna in device **10** may be affected by parasitic antenna elements such as parasitic element **58**. The impact of a parasitic element on antenna performance can be adjusted by adjusting the size and shape of the parasitic element. Dashed line **56** shows how parasitic antenna element material may be removed from parasitic antenna element **58** of antenna structures **24**. Dashed line **54** shows parasitic antenna element material may be added to antenna structures **24** (e.g., to enlarge an existing parasitic antenna element or to add a parasitic antenna element).

The examples of FIG. **4** are merely illustrative. In general, any suitable modifications may be made to antenna structures **24** to adjust the performance of antenna structures **24** in device **10**. Antenna performance may be adjusted by adding conductive structures, removing conductive structures, adding dielectric structures (e.g., adding plastic or other dielectrics to structures **24**), removing dielectric structures, changing the relative positions between structures within antenna structures **24**, deforming antenna structures **24**, adjusting electrical components such as fuses and antifuses within structures **24**, or making other antenna structure modifications.

Any suitable equipment may be used in making antenna structure adjustments to antenna structures **24**. As shown in FIG. **5**, for example, antenna structures **24** can be modified using a tool that adds material to antenna structures **24** such as material deposition tool **62** or other material adding tool. Tool **62** may include equipment for adding conductive and/or dielectric material to antenna structures **24**, as illustrated by additional material **64** on the right-hand side of FIG. **5**. Examples of material deposition (addition) tools **62** are ink-jet printers for depositing liquid material such as conductive ink, pad printing apparatus, screen printers, brushes or other tools for applying metallic paint or other conductive liquids, conductive tape application tools, electrochemical deposition tools, physical vapor deposition tools, laser processing tools (e.g., tools for performing laser direct structuring operations by sensitizing plastic carriers for subsequent electroplating), injection molding tools (e.g., tools for forming two-shot plastic carriers that include plastic shots with different metal affinities to allow selective metal deposition during electrochemical deposition or other suitable deposition processes), soldering tools for adding solder, welding tools for adding additional metal structures, etc.

FIG. **6** shows how antenna structures **24** may be customized using material removal tool **66**. Material removal tool **66** may be used to selectively remove metal structures or other structures within antenna structures **24**, as indicated by removed portion **68** of antenna structures **24** on the right-hand side of FIG. **6**. Examples of tools **66** that are suitable for removing material from antenna structures **24** include plasma cutting and etching tools, wet and dry etching tools, ion milling tools, laser trimming tools, milling machines, drills, saws, and other physical machining tools, etc.

As shown in FIG. **7**, antenna structures **24** may be customized using material deformation tool **70**. Material deformation tool **70** may, for example, apply localized heat from a laser or other heat source to cause substrate materials to swell, bend, or otherwise deform. As shown in the right-hand side of FIG. **7**, for example, use of material deformation tool **70** may create deformations such as deformation **72** in antenna structures **24**. Deformation **72** may be caused by heating, application of light, application of electrons or other particles, or application of other sources of energy.

As shown in FIG. **8**, a computer-controlled signal generator or other electrical adjustment tool **74** may be used to make electrical adjustments to antenna structures **24** by applying electrical signals to portions of antenna structures **24**. Electrical adjustment tool **74** may be for example, a computer-controlled voltage source or current source. Examples of components that may be configured using tool **74** include fuses and antifuses. Fuses are initially closed circuits that become open circuits when a sufficiently large electrical signal is applied (i.e., a current over the rating of the fuse to blow the fuse). Antifuses operate similarly, but initially form open circuits that are closed by application of sufficiently large electrical signals.

FIG. **9** shows how antenna structures **24** may be customized by removing material **68**. Material removal operations may be used to shorten the length of an antenna structure, to narrow the width of an antenna structure, to create an enlarged dielectric gap between adjacent conductive members, to change the geometry of a conductive structure in antenna structures **24**, or to otherwise make modifications to antenna structures **24**. FIG. **10** shows how antenna structures may be customized by removing material to produce a dielectric gap such as gap **68**. In the FIG. **10** example, antenna structures **24** initially include a solid conductive structure such as a strip of metal. As shown in the lower portion of FIG. **10**, following customization by removal of some of the strip of metal, a gap such as gap **68** has been formed that separates the strip into separate conductive pieces such as metal structure **24**A and metal structure **24**B.

FIG. **11** shows how antenna structures **24** may be customized by adding material **64** to extend the length of a conductor. Additional material may be added to antenna structures **24** to increase the length of a structure, to increase the width of a structure, to cause adjacent conductive structures to become closer to one another, to change the shape of a conductive antenna structure, etc.

FIG. **12** shows how antenna structures **24** can be customized to join separate antenna structures. In the FIG. **12** example, antenna structures **24** initially contain two separate antenna structures **24**A and **24**B. Following addition of material **64**, structures **24**A and **24**B are electrically joined to form a single conductive structure. Additional material **64** may be solder, material added by welding, conductive ink (paint), an additional customized structure that contains customized metal structures on a dielectric substrate, etc.

FIG. **13** shows how antenna structures **24** may be customized by blowing a fuse such as fuse **61**. In the example of FIG. **13**, fuse **61** initially has an unblown state and electrically shorts antenna structures **24**A and **24**B together. Following application of current using a tool such as electrical adjustment tool **74** of FIG. **8**, fuse **61** may be blow to form an open circuit (see, e.g., blown fuse **61'** in the lower portion of FIG. **13**). When the fuse is blown, the fuse forms an open circuit and no longer connects structures **24**A and **24**B to each other.

In the example of FIG. **14**, antenna structures **24** are being customized using antifuse **63**. Initially, antifuse **63** is in an open circuit state (the upper portion of FIG. **14**), in which structures **24**A and **24**B are not electrically shorted to each other through antifuse **63**. Following application of an electrical signal using electrical adjustment tool **74** of FIG. **8**, antifuse **63'** may be placed in its low-resistance state to electrically short conductive structure **24**A to conductive structure **24**B.

An illustrative antenna structure customization process that involves deforming antenna structures **24** is shown in FIG. **15**. Initially, structures **24** contain two planar members **82** and **84**, as shown in the cross-sectional side view of antenna structures **24** in the upper portion of FIG. **15**. Upper member **82** may be a metal layer. Lower member **84** may be a dielectric substrate such as a polymer substrate. Following application of heat or other forms of energy in region **80** (e.g., using material deformation tool **70** of FIG. **7**), the exposed portion of material in antenna structures **24** deforms (e.g., by swelling or bending upwards), forming deformed portion **72** in antenna structures **24**, as shown in the lower portion of FIG. **15**. The deformation of the antenna structures can affect antenna performance by changing the length of conductive structures, by altering the shape of conductive structures, by altering the distance between conductive structures, etc.

A flow chart of illustrative steps involved in manufacturing devices such as electronic device **10** of FIG. **1** that include custom antenna structures **24** is shown in FIG. **16**.

At step **86**, antenna structures **24** and other device structures can be formed according to nominal (not customized) specifications. During the manufacturing process of step **86**, parts for a particular design of device **10** and antenna structures **24** may be manufactured and collected for assembly. Parts may be manufactured by numerous organizations, each of which may use different manufacturing processes. As a result, there may be manufacturing variations in the parts that can lead to undesirable variations in the antenna performance for antenna structures **24** if not corrected. These performance variations may be characterized using test equipment such as network analyzers (e.g., vector network analyzers) and other radio-frequency test equipment and associated computer equipment. The test equipment may make measurements antenna frequency response and other performance measurements and may use these antenna performance measurements to determine how to customize the antenna structures to compensate for performance variations.

The test equipment may identify variations in antenna performance from desired performance levels by comparing measured performance data to curves of expected performance (e.g. high and low limit data) or may use other performance criteria. Based on identified deviations between actual and desired performance, the test equipment may ascertain which corrective actions should be taken when customizing antenna structures **24**. The test equipment may produce reports or other output data for use in manually making manufacturing adjustments to antenna structures **24** and/or may produce control signals that automatically adjust manufacturing equipment to customize antenna structures **24** (i.e., control signals or other output that directs the manufacturing equipment to make identified customizations).

At step **88**, manufacturing operations may be performed to customize antenna structures **24** in accordance with the corrective actions (customizations) identified during the operations of step **86**. Manufacturing operations may be performed to add conductive material and/or dielectric material to antenna structures **24** using material adding tools such as tool **62** of FIG. **5**. For example, the size and shape of conductive antenna resonating element structures, parasitic antenna elements, and ground plane structures may be changed by adding conductive material. Manufacturing operations may be performed to remove conductive and/or dielectric material using material removal tools such as material removal tool **66** of FIG. **6**. For example, an antenna resonating element, antenna ground, or parasitic antenna element may be adjusted in size and/or shape by removing conductive material. Tools such as material deformation tool **70** of FIG. **6** may be used in customizing antenna structures **24** by deforming conductive and/or dielectric structures in antenna structures **24**. Tools such as tool **74** of FIG. **8** may be used to make customizing electrical adjustments to electrical components such as fuses and antifuses.

By customizing antenna structures **24** using techniques such as these or other suitable manufacturing techniques, antenna structures **24** may be customized to compensate for the performance variations identified during the operations of step **86**. Following antenna structure customization, remaining manufacturing steps associated with manufacturing complete devices **10** may be performed (step **90**). During these steps, the customized version of antenna structures **24** may be installed within device housing **12**, antenna structures **24** may be coupled to transceiver circuitry **36** using transmission line **30**, and remaining components may be installed within device **10** to form a completed unit.

The foregoing is merely illustrative of the principles of this invention and various modifications can be made by those skilled in the art without departing from the scope and spirit of the invention. The foregoing embodiments may be implemented individually or in any combination.

What is claimed is:

1. A method of producing customized antenna structures for an electronic device using manufacturing equipment, comprising:

forming antenna structures for an electronic device using the manufacturing equipment;

identifying manufacturing variations in the antenna structures by measuring radio-frequency antenna performance of the antenna structures using the manufacturing equipment, wherein identifying the manufacturing variations comprises determining whether the antenna structures comprise two separate conductive structures separated by a gap;

identifying customizations to be made to the antenna structures to compensate for the identified manufacturing variations using the manufacturing equipment; and

making the identified antenna structure customizations to the antenna structures to produce customized antenna structures for the electronic device using the manufacturing equipment, wherein making the identified antenna structure customizations comprises adding conductive material that joins the two separate conductive structures in the antenna structures to produce the customized antenna structures.

2. The method defined in claim **1** wherein making the identified antenna structure customizations comprises adding dielectric material to the electronic device antenna structures.

3. The method defined in claim **1** wherein adding the conductive material comprises depositing conductive material with a material deposition tool.

4. The method defined in claim **3** wherein adding the conductive material comprises adding conductive material using a technique selected from the group consisting of: soldering, welding, applying conductive paint, and applying conductive tape.

5. The method defined in claim **1** wherein making the identified antenna structure customizations comprises removing dielectric material from the electronic device antenna structures.

6. The method defined in claim **1** wherein making the identified antenna structure customizations comprises removing conductive material from antenna structures.

7. The method defined in claim **6** wherein removing the conductive material comprises removing the conductive material with a material removal tool selected from the group consisting of: a laser trimming tool, an ion milling tool, a physical machining tool, and a plasma cutting tool.

8. The method defined in claim **6** wherein removing the conductive material comprises removing conductive material from a conductive antenna structure in the antenna structures to form two conductive structures separated by a gap.

9. The method defined in claim **1** further comprising:

with the manufacturing equipment, assembling the electronic device to include the customized antenna structures.

10. A method of producing customized antenna structures using manufacturing equipment, comprising:

forming antenna structures using the manufacturing equipment;

identifying manufacturing variations in the antenna structures by measuring radio-frequency antenna performance of the antenna structures using the manufacturing equipment;

identifying customizations to be made to the antenna structures to compensate for the identified manufacturing variations using the manufacturing equipment; and

making the identified antenna structure customizations on the antenna structures to produce customized antenna structures using the manufacturing equipment, wherein making the identified antenna structure customizations comprises bending material in the antenna structures to produce the customized antenna structures.

11. The method defined in claim **10** wherein deforming the material comprises bending at least one metal structure in the antenna structures.

12. The method defined in claim **10** wherein bending the material comprises applying heat to the antenna structures.

13. A method of producing customized antenna structures using manufacturing equipment, comprising:

forming antenna structures using the manufacturing equipment, wherein the antenna structures comprise a fuse;

identifying manufacturing variations in the antenna structures by measuring radio-frequency antenna performance of the antenna structures using the manufacturing equipment;

identifying customizations to be made to the antenna structures to compensate for the identified manufacturing variations using the manufacturing equipment; and

making the identified antenna structure customizations on the antenna structures to produce customized antenna structures using the manufacturing equipment, wherein making the identified antenna structure customizations comprises applying electrical signals to the fuse in the antenna structures.

14. A method of manufacturing customized antenna structures for an electronic device using manufacturing equipment, the method comprising:

forming antenna structures using the manufacturing equipment;

measuring radio-frequency performance of the antenna structures to identify manufacturing variations using the manufacturing equipment;

identifying customizations to make to the antenna structures to compensate for manufacturing variations using the manufacturing equipment;

making the identified customizations to produce customized antenna structures by removing conductive material from a conductive antenna structure in the antenna structures to form two conductive structures separated by a gap using the manufacturing equipment; and

manufacturing the electronic device to include the customized antenna structures.

15. The method defined in claim **14** wherein making the identified customizations comprises removing a portion of electronic device antenna structures to produce the customized antenna structures.

16. The method defined in claim **15** wherein removing the portion of the electronic device antenna structures comprises removing a portion of a conductive antenna resonating element to produce the customized antenna structures from a remaining portion of the conductive antenna resonating element.

17. The method defined in claim **15** wherein removing the portion of the electronic device antenna structures comprises removing a portion of an antenna ground conductor to produce the customized antenna structures.

18. The method defined in claim **14** wherein the customized antenna structures include a parasitic antenna element and wherein making the identified customizations comprises adjusting the parasitic antenna element.

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